DTIC QUALITY INSPECTED 2

SOCIETY OF AUTOMOTIVE ENGINEERS, INC.
Two Pennsylvania Plaza, New York, N. Y. 10001

LOW-COST FABRICATION TECHNIQUES FOR SOLID ROCKET NOZZLES

J. J. WARGA
AEROJET SOLID PROPULSION COMPANY

PLASTEC/14809

SOCIETY OF AUTOMOTIVE ENGINEERS

National Aeronautic and Space Engineering
and Manufacturing Meeting
Los Angeles, Calif.
October 5-9, 1970

700796

19960314 008

700796

LOW-COST FABRICATION TECHNIQUES FOR SOLID ROCKET NOZZLES

J. J. WARGA

AEROJET SOLID PROPULSION COMPANY

ABSTRACT

Savings of 50 percent can be achieved in ablative nozzles for 260-in.-dia solid rocket motors using present state-of-the-art materials. An optimum nozzle design with respect to cost and performance results from the use of a standard carbon-phenolic tape grade for the throat insert and canvas, carbon-silica and silica materials throughout the remainder of the nozzle.

INTRODUCTION

Since 1966, there has been a continuing effort to reduce the cost of large, reinforced ablative composite solid rocket nozzles through the use of inexpensive materials and low-cost fabricating techniques. The Aerojet-General Corporation has conducted evaluation programs on behalf of the Air Force and NASA; so has the Thiokol Chemical Corporation. Both the Air Force and NASA have sponsored the development and testing of low-cost materials systems. This paper reviews the processing techniques and the materials that have been evaluated during the past four years*; describes the capabilities and limitations; and discusses the means for effecting continued economies.

When, seven years ago, the Aerojet-General Corporation was selected to demonstrate the feasibility of manufacturing solid rocket motors with case diameters of 260 in., the data on the physical and mechanical properties of reinforced ablative plastic composites were sparse, and for the large sizes under consideration, were nonexistent. Thus, an important part of the demonstration program was the design and fabrication of the ablative nozzle and the verification of its performance. A material and process evaluation program was conducted to select the materials and define the processes to be used in the fabrication of the nozzles. Measurements of properties were made at room and elevated temperatures. Subscale motor tests, using 44-in. and 120-in.-dia motors, were conducted to substantiate the design criteria, the materials, the fabrication procedures, and to verify the ablative performance predictions of the full-size 260-in. nozzles. Short-length 260-in.-dia motors were successfully test fired in September 1965, February 1966, and June 1967.

The performance of the nozzles was satisfactory; the cost, however, was higher than was deemed desirable. Accordingly, evaluation of alternative, low-cost materials was initiated in the Fall of 1966. The potential cost savings can be visualized by reference to the overall dimensions. For example, the submerged type of nozzle most recently proposed for use in 260-in.-dia motors has a 7.5-ft-dia throat, an overall length of 25 ft, a diameter at the exit plane of 22.5 ft, and an ablative component weight of approximately 20 tons.

FABRICATION

TAPE WRAPPING - Molding tape for use in wrapping is manufactured by impregnating a fabric or mat reinforcement with a selected ablative plastic resin that has been diluted with a compatible solvent. Particulate or hollow fillers may be added to the resin mix. The impregnated reinforcement is passed through temperature-controlled towers to

* The information is available chiefly from technical and documentary reports with limited distribution.

remove the solvent and to polymerize the resin to some intermediate stage suitable for storage, handling, and further fabrication. The material--called "prepreg"--is slit into tapes and broadgoods and shipped to the component fabricators.

Part fabrication is performed by wrapping the prepreg tapes on a metal mandrel, with the plies of tape aligned at some desired angle to the flame surface of the finished part. For mechanical retention of each ply and for simplicity in fabrication, nozzle components in the entrance and throat sections have ply orientations parallel to the nozzle centerline. Angled wraps require the use of a bias-fabric tape to produce the desired deformation and compaction during wrapping; the parallel wraps use straight tapes.

Wrapping may be performed in either the horizontal or the vertical position. During wrapping, illustrated schematically in Figure 1, the prepreg tape is heated prior to layup, using hot-air jets or radiant heaters. This softens the resin for interply bonding and makes the prepreg more formable under the pressure rollers. The tape temperature, roller pressure, rotational speed and billet temperature are held within fairly narrow limits to control the as-wrapped density.

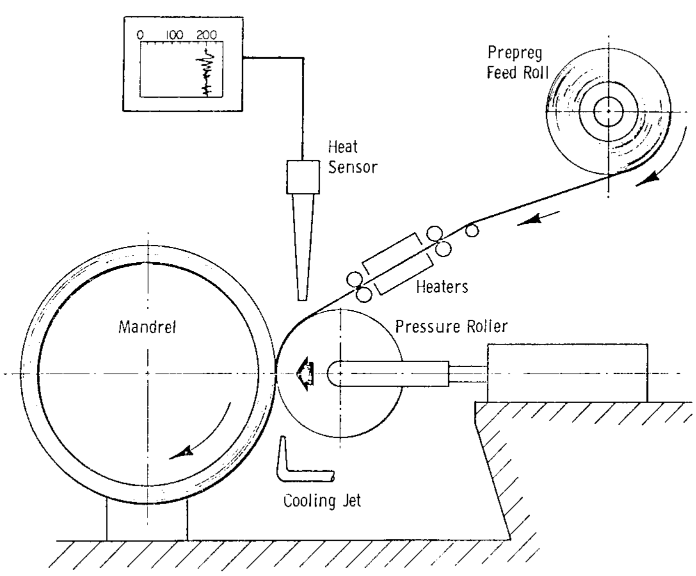

Figure 1 - Schematic of Wrapping Process

After the preform has been wrapped, it is covered with a porous fabric (bleeder cloth), enclosed in an impervious bag and cured by one of two alternative procedures. If the flame liner is to be overwrapped with another ablative prepreg of greater thermal insulating value, the preform is "debulked"—compacted and partially cured at full pressure and temperatures between 165 and 180°F—so that a smooth surface may be machined prior to application of the overwrap. If the flame liner is not to be insulated, the preform is cured at full pressure and the required resin polymerization temperature. During curing (and debulking), vacuum is maintained in the enveloping bag and the polymerization reactants are drawn off through the bleeder cloth.

Pressure during debulking and curing may be applied by any one of several means. Hydroclaves, using hot water at pressures of up to 1000 psi; autoclaves using heated gas at pressures of up to 350 psi; and nylon shrink tapes exerting hoop tensions to 150 psi all have been used.

Analysis of the separate steps involved in fabrication by tape wrapping points the way for cost reductions. One obvious step is to reduce the wrapping times by increasing the tape speed, or by applying multiple layers of tape or by using thicker tapes than normal. This last approach has been successfully demonstrated with both carbon and silica fabric prepregs[1, 2]*. Wrapping times have been reduced by as much as 55% by using double-thick tapes.

Economies can be effected in capital equipment costs by reducing the cure pressure requirements. Figure 2, taken from a recent study of the effects of ablative discrepancies[3], shows how the regression rate in a carbon reinforced composite throat insert changes with the density.

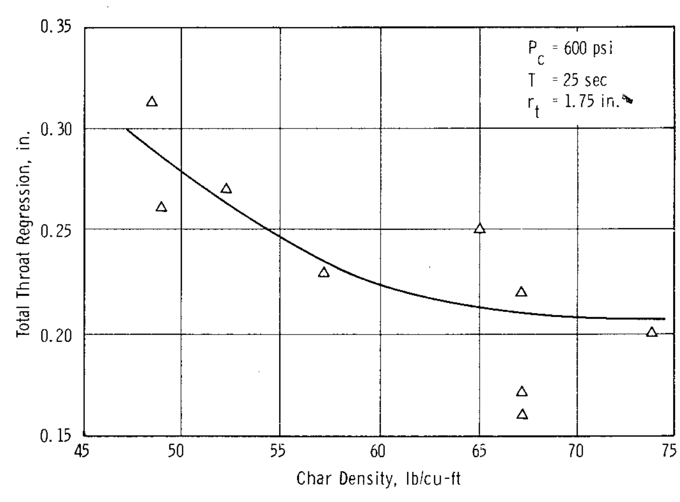

Figure 2 - Effect of Char Density on Regression of Carbon Reinforced Composites in Throat Regions

Based on the attainment of a minimum char density of 64 lb/cu ft, autoclave curing at a pressure of 125 psi or less could be used for the high-angled wraps in and near the throat. In the nozzle exit section, where heat fluxes are

*Numbers in parentheses designate references at end of paper.

lower and the ply orientation is parallel to the centerline, the regression rate is unaffected by density[3]. Figure 3 shows the changes in regression rate in a silica phenolic exit cone as a function of char density. It appears that vacuum pressures of 25 to 27 in. of mercury could be used for curing. In this case, the heat for curing is supplied by a recirculating hot oven, which is less costly than autoclaves.

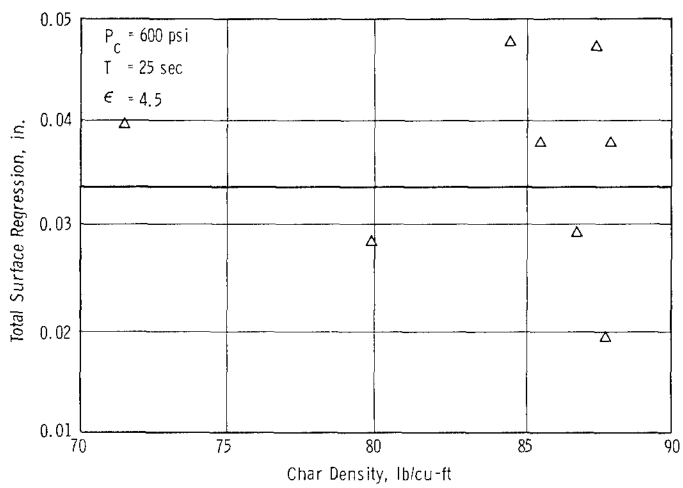

Figure 3 - Effect of Char Density on Regression of Silica Reinforced Composites in Exit Sections

COMPRESSION MOLDING - Compression molding is a high volume, low-cost method of fabrication that has been used in manufacturing small and medium-sized nozzle components. Metal dies, mounted in hydraulic or mechanical presses, are used. The parts are either net molded to size or formed into billets requiring only nominal machining to size. Molding pressures of up to 8000 psi have been used. Steam coils and electric strip heaters embedded in the dies are used for heating to the required curing temperatures. The molding compounds can be loaded, in accurately weighed batches, into either a hot or cold mold.

In general, any broadgoods material that can be tape wrapped can also be compression molded by a modification in the resin content. The fabric reinforcement, however, is chopped into 1/4-in. or 1/2-in. squares so that it will flow into the die cavity during molding. In addition, compression molding compounds are prepared from chopped roving, chopped fibers, and granules. For this reason, molding compounds are generally not so expensive as the tape grades.

In the manufacture of a molded part, the ability of the molding compound to fill the die cavity and produce a sound, homogeneous cross section is measured by its flow characteristics and its bulk factor. In ablative molding compounds the flow ranges from 4 to 20% and the bulk factor from a low of 4 to 1 to a high of 20 to 1. Because of the ratio of length to section thickness in the 260-in. nozzle components, it is questionable that any parts but the throat inlet and throat could be made as single-piece moldings.

It has been pointed out that molding pressures as high as 8000 psi have been employed for curing ablative nozzle parts. Carbon-fiber-reinforced molding compounds have been found to perform satisfactorily after having been molded at 500 psi[1]. Graphite particle molding compounds have exhibited satisfactory performance when molded in the range of 850 to 1000 psi[2]. Molding at these pressures decreases the need for large press capacity and thus reduces facility expenditures. In addition, the possibility of fabricating a finished part in 48 to 72 hr, instead of four to seven weeks, makes molding the throat in one piece extremely attractive.

Facility and tooling costs may also be reduced if the design of the entrance and exit sections can be optimized so that only a few dies are used to produce molded segments that can be assembled into an interlocking pattern to form the full-sized components. Subscale* throats and exit cones with this type of joint pattern have been evaluated[2, 4]. No differential erosion was observed at the axial joints and only a small amount was observed at the circumferential joints. A present program**, financed by NASA, will investigate the performance of jointed parts in the entrance areas of the nozzle.

Should compression molded parts prove to be demonstrably cheaper to fabricate than wrapped parts, then it may be possible to reduce the curing time drastically by the use of radio-frequency (RF) heating. The method has been used for moldable plastic resins and appears to be feasible for ablative parts[5].

CASTING, TROWELLING AND SPRAYING - Casting has been evaluated for applicability to 260-in.-dia nozzle parts[2]; the remaining two techniques are under investigation. Facility and equipment costs for these fabricating techniques are nominal, since pressures during curing very seldom exceed 27 in. of mercury. Molds are used to cast billets or shaped parts; reinforcements such as honeycomb or wire mesh or contoured forms are used during troweling or spraying operations.

Ablative materials for these techniques range from the phenolic base to furfuryls to silicones, acrylonitriles and

* 44-in.-dia motor

**NAS3-12064, "Development of Low-Cost Fabrication Techniques for Solid Rocket Ablative Nozzles".

polysulfides, blended with epoxies and polyamides. Structural reinforcements and fillers include silica, carbon, graphite, glass, rayon and coke in the form of powders, granules, fibers and microballoons.

MATERIALS

During the initial development phase of the 260-in.-dia motor program, the ablative nozzle materials exhibiting the best performance (and consequently those of least risk) were the carbon, graphite and silica fabric-reinforced composites. All three are elevated-temperature conversion products, the carbon and graphite fabrics being manufactured from a rayon precursor and the silica from a glass. Because of the high temperatures required for conversion, the shrinkage that occurs during conversion, and the low yields, particularly with the rayon precursor, the reinforcement material costs are high. Consequently, a great deal of effort has been spent in investigating alternative, low-cost materials.

Table I shows the Cost/Performance Effectiveness (C/PE)* of alternative tape materials that have been evaluated in nozzle assemblies attached to 44-in.-dia motors. The most satisfactory tape replacements for the original silica/phenolic composites were found to be Kraft paper, canvas duct and crocidolite asbestos. The most satisfactory tape replacements for the original carbon/phenolic composite were carbon-silica and silica. (The carbon-silica fabric is also a conversion product in which the precursor yarns are continuous multifilaments spun from viscose dopes containing alkali-soluble ceramic lattice formers. The particular grade considered was a codeposited mixture that yielded 65% silica and 35% carbon after conversion.) Examination of Table I leads to the conclusion that, strictly on the basis of C/PE, a 260-in. nozzle could be fabricated from codeposited carbon-silica and canvas duck phenolic prepregs at an overall savings of 30%.

Table I - Cost/Performance Effectiveness of Tape Materials

Component	Material: Original	Material: Replacement	C/PE
Approach	Silica	Kraft Paper	3.33
		Crocidolite Asbestos	1.53/2.18
		Canvas	1.38
Entrance Cap	Carbon	Carbon-Silica	1.48
		Kraft Paper	1.48
Inlet	Carbon	Carbon-Silica	1.40
Throat	Carbon	Carbon-Silica	1.14/1.28
Throat Extension	Carbon	Silica	1.28
Exit Extension	Silica	Crocidolite Asbestos	1.25/1.45
		Canvas	1.15/1.27

Materials from Reference 1.

Compression molded materials have not been evaluated to the same extent as the tape materials. As of the present, only two compression-molded materials have been reported as having been evaluated in 44-in. nozzles. One is a carbon-fiber-reinforced compound; the other is a graphite particle material. Table II shows the cost/performance comparison with the carbon tape throat material that was originally used. Both materials were molded at pressures below 1000 psi and both exhibited regression rates slightly higher than the tape material originally used. The higher C/PE of the molded graphite particle material is a function of the very low material cost (reportedly on the order of $0.75 per lb).

Table II - Cost/Performance Effectiveness of Molded and Cast Materials

Component	Material: Original	Material: Replacement	C/PE
Entrance Cap	Carbon	Carbon Fiber	1.07*
Throat	Carbon	Graphite Particle	1.28**
Exit Extension	Silica	Graphite Particle	2.33**

* From Reference 1
**From Reference 2

One casting material, a graphite particle grade cured under vacuum at 170°F has been evaluated in 44-in.-dia motors[2]. The C/PE, also shown in Table II, was calculated to be as high as 2.33 when the material was used in exit sections. There have been no published reports of the evaluation of trowelable or castable materials in nozzles attached to 44-in.-dia solid rocket motors.

NOZZLE-MOTOR COST TRADEOFF

There is no question but that the cost of 260-in. ablative nozzles can be reduced by the use of alternative, low-cost materials. These low-cost materials, however, exhibit in most cases higher material loss rates than the original

* C/PE is based on the volume of the ablative material that undergoes erosion and charring. It is the ratio of the cost of the standard material divided by the cost of the test material. See the Appendix for explanation of its meaning.

(baseline) nozzle materials. The material loss rate is particularly significant at the nozzle throat; increases in the throat area result in decreases in chamber pressure, leading to lower than planned thrust levels unless compensating changes are made. Compensating changes may introduce additional propellant weight and/or changes in the propellant grain configuration; these add to the chamber size and produce higher overall motor cost. The overall effect of the compensating changes can be evaluated. In one such evaluation in which the objective was to maintain an equal payload capability in 260-in. boosters, it was found[6] that each 1 mil/sec increase in the booster nozzle throat erosion rate over the baseline rate of 6 mils/sec added $25,000 to the booster motor cost.

The tradeoff between increased motor cost and nozzle throat erosion can be used to select a nozzle configuration that is optimum with respect to meeting booster payload requirements at minimum cost. Table III shows the ablative materials proposed for use in four alternative 260-in. nozzle designs compared to a baseline nozzle with materials chosen on the basis of known performance reliability. The

Table III - Alternative 260-In. Nozzle Configurations

Component	Baseline Material	Alternate Materials Nozzle 1	Nozzle 2	Nozzle 3	Nozzle 4
Submerged Liner	Silica (8.65)	Asbestos (2.25)	Canvas (3.00)	Canvas (3.00)	Canvas (1.75)
Nose	Carbon (24.65)	C-Si (15.75)	Canvas	Silica (5.93)	Canvas (3.00)
Inlet	Carbon	C-Si	Silica (5.93)	C-Si (15.75)	Graphite Particle (0.75)
Throat	Carbon	C-Si	Silica	Carbon (22.40)	Graphite Particle
Throat Extension	Carbon	C-Si	Silica	C-Si (15.75)	Carbon (15.40)
Forward Exit Cone	Carbon (22.00)	C-Si (13.25)	Silica (5.43)	Silica (5.43)	Carbon (14.50)
Aft Exit Cone	Silica (6.00)	Canvas (1.75)	Canvas (1.75)	Canvas (1.75)	Graphite Particle
Insulation	Silica	Canvas	Canvas	Canvas	Canvas

costs of the prepreg and moldable materials are parenthetically noted in the table; they reflect bulk prices as of March 1970. Figure 4 shows the added motor costs resulting from the use of the different throat insert materials; the erosion rates are derived from heat-transfer analyses. Table IV summarizes the cost tradeoff among the five nozzle designs.

Maximum overall cost savings ($219,670) were calculated to result from the use of alternate nozzle 3, in which a standard carbon-phenolic prepreg tape was used to fabricate the throat insert only and other, lower-cost materials were used in the remainder of the nozzle. Since a standard carbon-phenolic was used, the throat erosion was unchanged

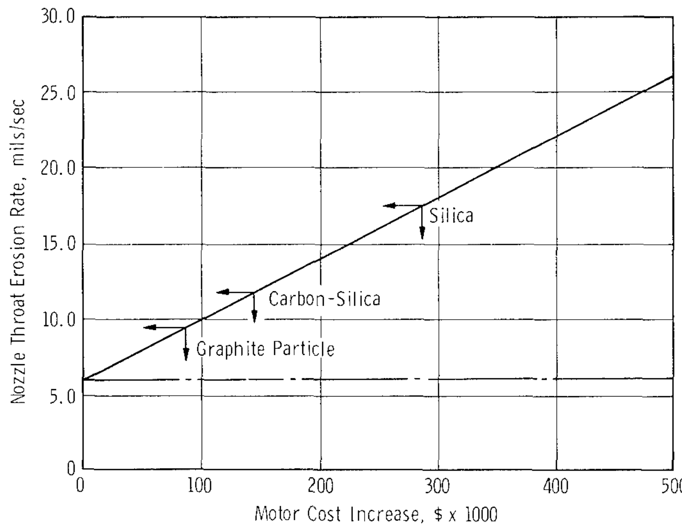

Figure 4 - Trade-off of Throat Erosion Rate and Motor Cost

from the baseline condition and no added motor costs were required. Cost savings only slightly less ($215,815) were achieved through the use of a graphite particle throat and exit cone (alternate nozzle 4). In this case, the nozzle material cost saving was greatest ($305,815), but an added motor cost of $90,000 resulted from the poorer erosion resistance of the graphite particle material. The silica nozzle (alternate nozzle 2) exhibited the least amount of overall cost savings.

Table IV - Cost Trade-off for 260-In. Motors and Nozzles

Nozzle	Total Nozzle Material Costs	Nozzle Material Cost Savings	Added Motor Cost (Equal Payload)	Cost Savings
Baseline	434,490	---	---	---
Nozzle 1 (Carbon-Silica)	215,250	219,240	140,000	79,240
Nozzle 2 (Silica)	130,890	303,600	282,000	21,600
Nozzle 3 (Carbon)	214,820	219,670	-0-	219,670
Nozzle 4 (Graphite Particle)	128,675	305,815	90,000	215,815

MATERIALS BEING EVALUATED

In a current program sponsored by NASA*, preliminary evaluation of material performance has been completed, using ablative nozzles with a throat diameter of 1.8 in. Table V lists materials found to be suitable for continued evaluation in nozzle assemblies attached to 44-in.-dia motors. Of particular interest are two low-cost carbonaceous throat materials.

* Contract NAS3-12064.

One is a molding compound that incorporates a carbon fiber converted from a spun pitch precursor. The yield conversion is higher than that of the customary rayon precursor, and for this reason one would expect reduced material costs. The reinforcement can be supplied in all other standard forms - fabric, mat and paper - as well as paper.

The other, listed as "Low-Cost Carbonaceous" in Table V is a graphite particle material suitable for molding and casting. It is a recent development, intended to provide improved fabricating characteristics over the material listed in Table II.

Table V - Candidate Materials for Evaluation in 44-In. Motors

Material Type	Fabrication Technique	Location
Coke/Furfuryl Alcohol	Casting	Nose
Extruded Fibertape	Wrapping	Nose, Exit
Silicone	Casting, Spraying	Nose, Exit
Phenolic-Epoxy	Casting	Nose, Exit
Low Cost Carbonaceous	Casting, Molding	Throat
Carbon*/Epoxy Novalac	Wrapping	Throat
Spun Pitch/Phenolic	Molding	Throat
Carbon-Silica/Epoxy Novalac	Spraying	Exit

*86% Carbon, "alloyed" with boron and phosphorus.

CONCLUSIONS

Maximum overall cost savings for 260-in.-dia motor nozzles can be achieved by using carbon or graphite reinforcements in the throat inserts. Other alternative, lower-cost materials reduce the nozzle cost, but the sacrifices in performance due to increased throat erosion produce counterbalancing increases in the overall motor cost to maintain equal payload boost capability. For continued cost reductions, the most promising approaches are (1) to reduce the cost of conventional carbon or graphite reinforcements for ablative composites, and (2) to improve the resistance to erosion of the low-cost graphite particle molding compounds.

REFERENCES

1. Warga, J. J. et al., Evaluation of Low-Cost Materials and Manufacturing Processes for Large Solid Rocket Nozzles, AFRPL-TR-67-310, December 1967. This has been excerpted and published in the Science of Advanced Materials and Process Engineering Series, Vol. 15, pp 435-444. Copyright 1969 (SAMPE).
2. Mathis, J. R. and C. R. Larrabee, Development of Low-Cost Ablative Nozzles for Solid Propellant Rocket Motors, NASA CR-72641, February 1970.
3. Warga, J. J., Investigation of Effects of Ablative Discrepancies on Nozzle Performance Reliability, NASA CR-72702, May 1970.
4. Lampman, J. J., J. J. Warga, and H. O. Davis, Deviation Nozzle Program, AFRPL-TR-68-81, June 1968.
5. King, C. B., Dielectric Processing for Low-Cost Ablation Heat Shields, Science of Advanced Materials and Process Engineering Series, Vol. 15, pp 445-453.
6. Savage, E. E., Optimization of 260-in. Diameter Motor with Low-Cost Materials, Report NAS7-513-SR-19, June 1970.

COST/PERFORMANCE EVALUATION

During service material is lost from the flame surface of a reinforced plastic nozzle component by regression. In addition, charring occurs below the regressing surface as heat is absorbed and the resin plastic decomposes. In designing an uncooled reinforced-ablative-plastic nozzle component, therefore, the minimum section thickness of the part must be as great as the expected regression and char depths plus some additional amount required for insulative and structural purposes. In the following discussion, only the regression and char layers are considered to contribute to the performance. Measurements of the char depth are made from original flame surface to the limit of the char and include the material lost by regression. The volume of material bounded by the original flame surface and the char line is designated the performance effective volume (PEV). This volume of material has a value which includes the variable material and fabrication costs associated with manufacturing the finished component. The cost of the performance effective volume is:

$$\text{Cost} = \text{PEV}\ (M + F), \qquad \text{(Equation 1)}$$

where M and F are the material and fabrication costs expressed as dollars per unit volume.

1. Determination of Unit Material Costs (M)

A typical nozzle component is machined from a molded billet. The cost of the material required to make the part, neglecting any scrap losses during wrapping, is equal to the volume of the billet (V_B), multiplied by the as-molded density (ρ) multiplied by the prepreg cost (C_p).

$$\text{Cost of Material} = V_B \times \rho \times C_p \text{ or,} \qquad \text{(Equation 2)}$$

$$\text{Cost of Material} = (\text{cu in.}) \ \frac{\text{lb}}{\text{cu in.}} \ \frac{\$}{(\text{lb})}$$

$$= \$$$

The unit cost of the material (i.e., the value of the material in the finished part, since the finished part does all the work) is equal to the total material cost divided by the volume of the finished part,

$$M = \frac{\text{Material Cost}}{V_f} \quad \text{or,}$$

$$M = \frac{V_B \times \rho \times C_p}{V_f} \qquad \text{(Equation 3)}$$

$$= \$/\text{cu in.}$$

2. Determination of Unit Fabrication Costs (F)

Various elements of labor are expended in making the finished test components. These are separated as follows:

a. Wrapping Costs

The wrapping cost is a function of the tape speed, the thickness of the plies, and the amount of compaction between the as-wrapped and cured billets. No wrapping costs are considered for compression molded parts or cast parts.

b. Bagging Costs

The cost of enveloping the as-wrapped billet and mandrel is considered to be a constant for each specific part that is autoclave or vacuum bag cured. Compression-molded or cast parts have no associated bagging costs.

c. Curing Cost

Curing costs include the labor costs prorated to autoclave, vacuum-bag (oven) or press operations.

d. Machining Costs

Machining costs are estimated on the ease of material removal. In general, the phenolic-resin-bonded composites require the same type of tooling and handling and the machining rates are similar. The elastomeric V-44 sheeting was much more difficult to machine and its machining cost was higher than that of any of the other test materials. The machining costs of the one-piece entrance caps were prorated.

e. Inspection Costs

Finished parts are inspected for surface and internal quality and for dimensions. The inspection procedures are the same regardless of the fabrication technique used.

The unit fabrication cost of each component, therefore, is the sum of all labor items involved in its fabrication divided by the volume of the finished part.

$$F = \frac{C_w + C_b + C_c + C_m + C_i}{V_f} \qquad \text{(Equation 4)}$$

$$= \$/\text{cu in.}$$

3. Determination of the Performance Effective Volume (PEV)

Experimentally, the regression and char depths are measured after test. If these are to be transposed to other nozzle designs, a scaling factor may be used (applicable if the propellant is the same).

$$\frac{\dot{a}}{\dot{a}_o} = \left(\frac{P}{P_o}\right)^{0.8} \left(\frac{D_o}{D}\right)^{0.2} \left(\frac{\Delta_t}{\Delta_{t_o}}\right) \qquad \text{(Equation 5)}$$

where P_o, D_o, and Δ_{t_o} are the experimental chamber pressure, nozzle diameter and firing duration, respectively.

Analytically, alternative nozzle designs can be compared by calculating regression and char depths by heat transfer techniques.

In either case, the total volume of decomposed material (PEV) is calculated, using graphical or geometrical techniques.

The cost of the decomposed material in each nozzle component, equation 1, is the product of the performance effective volume and the unit material and fabricating costs. This cost may be compared to the cost of the materials used in any standard nozzle as follows:

(Equation 6)

$$C/PE = \frac{\text{PEV (M + F) for Standard Material}}{\text{PEV (M + F) for Test Material}}$$

to yield a dimensionless number that is greater than one for the more effective materials and less than one for the less effective materials.